# Facies analysis and depositional environments of a storm-dominated, temperate to cold, mixed siliceous–carbonate ramp: the Permian Kapp Starostin Formation in NE Svalbard

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A facies model of the Permian Kapp Starostin Formation assigns various facies to specific depositional environments and thus shows the detailed spatial and temporal development of a temperate, mixed siliceous-carbonate ramp from the upper Cisuralian (Artinskian) into the Lopingian (Changhsingian). Calcareous, partly glauconitic and generally well-sorted sandstones are interpreted to represent shallow-marine sand flats within the most proximal, foreshore to shoreface areas of the inner ramp. These sediments indicate the uplift of a terrestrial, siliciclastic source area probably to the north or northeast of the study area. Highly diverse, commonly strongly silicified, skeletal limestones contain a typical heterozoan biotic assemblage, marked by a varying abundance of brachiopods, bryozoans and crinoids, as well as siliceous sponge spiculae. The carbonateproducing biota shows a specific distribution within the open-marine areas of the inner to mid ramp, where the bioclastic debris was reworked, redistributed and washed together by waves, tides and periodically occurring storms. While sandy brachiopod shell banks (coquinas) were mainly present within the inner ramp, bryozoan and crinoidal detritus accumulated within more distal areas, originating from scattered build-ups at the outer edge of the mid ramp. Spiculitic cherts, the most prominent facies of the Kapp Starostin Formation, are formed by the accumulation of abundant siliceous sponge spiculae, representing the major silica factory of the shelf. These deposits have the widest distribution, ranging from the inner ramp (light-coloured, massive to nodular cherts) around the fair-weather wave base to deeper-marine, outer ramp areas below the stormweather wave base (dark-coloured, bedded to massive cherts). Finely laminated to massive black shales generally indicate the most distal, deepmarine, toe-of-slope and basinal areas of the outer ramp, below the storm-weather wave base. The sediments originate from the accumulation of fine-grained, terrigenous matter under quiet-water conditions. The local preservation of primary lamination points to oxygen-depleted conditions, while bioturbation at other levels indicates the presence of bottom-feeding organisms under well-oxygenated conditions. The various facies were deposited on a stable, shallow submarine ramp marked by a subdued relief, gently sloping towards the south. The strata are arranged into four stacked parasequences (shallowing-upward cycles), which are interpreted as the result of short-term, possibly glacio-eustatic sea-level fluctuations superimposed on a long-term sea-level fall.

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# Introduction

Sedimentary bedrock of Permian age records an exceptional time period in Earth history, characterised by fundamental climatic, oceanographic and environmental changes. Svalbard, comprising a part of an epicontinental shelf sea at the northern margin of Pangaea, drifted from approximately 25°N in the Late Carboniferous to around 45° in the Late Permian (Scotese & Langford, 1995; Ziegler et al., 1997; Golonka, 2002). The shelf was arranged into a series of platforms and basins, which are exposed today in various circum-Arctic regions, e.g., eastern North Greenland (Wandel Sea Basin), the Barents

Sea (Finnmark Platform, Stappen High), Arctic Canada (Sverdrup Basin) and Russia (Timan–Pechora Basin). All of these areas record a prolonged time period, termed the Permian Chert Event (Beauchamp & Baud, 2002), during which massive chert successions accumulated while temperate- to cold-water conditions prevailed within the shelf seas of the northern hemisphere. Marine warmwater carbonates disappeared completely during this ca. 30 Myr-long period (Artinskian–Changhsingian), and were replaced by temperate- to cold-water depositional systems. The latter are marked by the predominance of siliceous sponges, whereas carbonate-producing organisms played only a minor role within the shelf ecosystems. The profound change from warm-water to temperate- and possibly cold-water environments has been associated with a number of palaeogeographic (e.g., closure of the Ural Ocean during the northward drift and final consolidation of Pangaea) and palaeoceanographic changes (e.g., upwelling of cold, nutrient-rich deep waters, salinity changes, anoxia, ocean acidification; Beauchamp, 1994; Stemmerik & Worsley, 1995; Beauchamp & Baud, 2002; Reid et al., 2007; Beauchamp & Grasby, 2012).

On Svalbard, Permian strata, consisting of the upper part of the Gipsdalen Group (Early Carboniferous to Early Permian), the Bjarmeland Group (Early Permian, restricted to Bjørnøya) and the Tempelfjorden Group (Early to Late Permian), are well exposed within a number of areas. Deposits of the Gipsdalen Group (Serpukhovian-Artinskian) mainly consist of carbonates and evaporites, representing a restricted- to open-marine, warm-water setting, marked by broad sabkhas, evaporite basins and carbonate platforms. The strata comprise a fully photozoan (Wordiekammen Formation) to reduced photozoan/ heterozoan assemblage (Gipshuken Formation, Blomeier et al., 2011). The strata of the overlying Tempelfjorden Group (Artinskian-?Changhsingian), on the contrary, are dominated by spiculitic cherts, as well as black shales, partly glauconitic sandstones and strongly silicified limestones as minor lithologies. The deposits reflect a generally deeper, temperate- to cold-water setting, comprising open-marine, shallow nearshore, to deeper offshore areas of a storm-dominated, mixed siliceouscarbonate shelf. A fully heterozoan biotic assemblage consists of siliceous sponges as the main silica factory and bryozoans, brachiopods and echinoderms as minor carbonate producers. Both lithostratigraphic groups are separated by a major unconformity (disconformity) comprising an Early Permian (Artinskian) hiatus, which resulted from the subaerial exposure of extended shelf areas and the subsequent erosion of the uppermost Gipsdalen Group strata with a renewed transgression at the beginning of the Tempelfjorden Group sedimentation (Ehrenberg et al., 2001; Blomeier et al., 2011).

Since the Tempelfjorden Group was defined by Cutbill & Challinor (1965), a number of publications have discussed the varied lithology, faunal assemblages, local and regional geological development, depositional environments, biostratigraphy and the sequence stratigraphic architecture of the strata (Burov et al., 1965; Szaniawski & Malkowski, 1979; Hellem, 1980; Knag, 1980; Biernat & Birkenmajer, 1981; Cutler, 1981; Lauritzen, 1981; Malkowski, K., 1982; Nakamura et al., 1987; Fredriksen, 1988; Henriksen, 1988; Stemmerik, 1988; Nakrem, 1988, 1991, 1994; Mangerud & Konieczny, 1991, 1993; Nakrem et al., 1992; Bottolfsen, 1994; Mangerud, 1994; Saalmann, 1995; Dallmann et al., 1999; Buggisch et al., 2001; Ehrenberg et al., 2001; Hüneke et al., 2001; Carmohn, 2007; Chwieduk, 2007; Grundvåg, 2008; Groen, 2010; Collins, 2012). However, uncertainties still exist with respect to age constraints, the regional

and local palaeogeography, and the lithostratigraphic arrangement of the group.

This article presents a comprehensive facies study of the Tempelfjorden Group (Kapp Starostin Formation) in NE Svalbard. Four vertical sections with a thickness from around 80 to 100 m were measured and outcrop observations combined with detailed microfacies studies. The latter enables the characterisation of a number of depositional environments defined by specific facies associations and their interpretation in terms of shelf position (distal/proximal), water depth (intertidal/ deeper submarine) and energy level (high/low). By identifying and correlating depositional cycles and their stacking pattern at each section location, the overall cyclostratigraphic architecture of the strata and the spatial and temporal development of the shelf area are discussed. Facies analysis proves a powerful tool to interpret both depositional environments and the palaeogeographic and cyclostratigraphic development of the Permian strata of Svalbard.

# Regional geological setting and lithostratigraphy of the Tempelfjorden Group

Late Palaeozoic bedrocks crop out within the entire Svalbard archipelago with superb exposures on Spitsbergen and Nordaustlandet complemented by small but important exposures on Barentsøya, Edgeøya and Bjørnøya (Fig. 1). While the sedimentary strata along the west coast of Spitsbergen are strongly deformed, steeply dipping and commonly thrusted (West Spitsbergen Fold Belt), outcrops within central and NE Spitsbergen as well as Nordaustlandet show mostly undeformed strata, with only gently dipping or horizontal bedding.

The Permian sedimentary record within NE Svalbard (NE Spitsbergen, Nordaustlandet) comprises two major lithostratigraphic units, the Early Carboniferous to Early Permian Gipsdalen Group (Serpukhovian-Artinskian) and the Early to Late Permian Tempelfjorden Group (Artinskian-?Changhsingian; Fig. 2). Both the lower and upper boundaries of the latter are distinct and sharp. The boundary to the underlying Gipsdalen Group is marked by a major hiatus and shows a sharp facies change from warm-water carbonates and evaporites to mixed siliceous-carbonate deposits (Blomeier et al., 2011). The boundary to the overlying, Early to Middle Triassic Sassendalen Group is characterised by the sharp change to fine-grained, marine siliciclastics such as black shales, siltstones and minor sandstones, combined with the termination of biotic deposits such as spiculitic cherts and bioclastic limestones. Controversy surrounds the transition into the Triassic, which is either conformable and marked by a condensed succession, or might comprise a major unconformity and hiatus. In this connection, the stratigraphic location of the Permian/Triassic boundary,



*Figure 1.* General geological map of the Svalbard archipelago (Bjørnøya excluded), indicating the section locations within NE Svalbard (Z1, S1, H1, E1). Note that all sections are located on the Eastern Svalbard Platform, a tectonic element east of the Lomfjorden Fault Zone.

which currently is defined at the sharp lithological boundary of the Tempelfjorden Group to the overlying Sassendalen Group, is also a topic of ongoing discussion (Steel & Worsley, 1984; Mørk et al., 1989; Stemmerik & Worsley, 1989; Mangerud & Konieczny, 1993; Mangerud, 1994; Stemmerik, 1997; Wignall et al., 1998; Ehrenberg et al., 2001; Nakrem et al., 2008; Dustira et al., 2013).

In most of Svalbard, the Tempelfjorden Group consists solely of the Kapp Starostin Formation. Only within the southernmost areas of Spitsbergen and on Bjørnøya the formation is replaced by the contemporaneous Tokrossøya Formation (Hornsund), and Miseryfjellet Formation (Bjørnøya), which both formed in discrete depositional basins marked by specific sedimentological and palaeogeographical developments (Dallmann et al., 1999; Fig. 2).

The Kapp Starostin Formation shows strongly variable thickness and lateral facies changes, implying a stable marine shelf characterised by a pronounced palaeobathymetry from deeper, basinal depocentres to



*Figure 2.* Permian time-scale (ICS, 2012), global sea-level curves and climate (yellow = warm; blue = temperate climate; Haq & Schutter, 2008) and modified lithostratigraphic system of Svalbard (Dallmann et al., 1999). Currently, considerable uncertainties exist with respect to age datings of the Tempelfjorden Group and its lithostratigraphic sub-units. SG = Sassendalen Group; Mb = Member.

shallow platform areas, controlling local sedimentation. As no major tectonic activity has been reported from the Permian on Svalbard, the local variations in thickness and facies might be related to the existence of a number of pre-existing, structural elements, inherited from the reactivation of major tectonic lineaments during the Early Carboniferous, and the subsidence of a series of elongated, narrow, rift basins (St. Jonsfjorden Trough, Inner Hornsund Trough, Billefjorden Trough and Lomfjorden Trough) bounded by adjacent highs (Sørkapp-Hornsund High, Nordfjorden High, Ny Friesland High; Steel & Worsley, 1984; Dallmann et al., 1999). Accordingly, the local thickness of the Kapp Starostin Formation varies substantially, from a maximum of 460 m in central Spitsbergen (with 380 m at its type section in Festningen, outer Isfjorden) to only a few metres in the Hornsund area. Farther south (Sørkapp Land), the strata completely wedge out against the margins of the Sørkapp-Hornsund High, a positive structural element, which remained emergent and acted as a terrestrial source area throughout the entire Permian.

The varied sedimentology and palaeogeography of Svalbard's Permian depositional basin is expressed in the internal lithostratigraphic arrangement of the formation (Fig. 2). In most areas on Spitsbergen (apart from Brøggerhalvøya in the northwest of the island) and on Nordaustlandet, the basal part of the Kapp Starostin Formation is formed by the Vøringen Member, which

comprises a prominent, up to 40 m-thick (Dallmann et al., 1999) succession. The member consists mainly of partly silicified, locally sandy, fossiliferous or lithoclastic limestones and allochemical sandstones, featuring a diverse, fully heterozoan biotic assemblage mainly consisting of brachiopods, with lesser amounts of bryozoans, echinoderms and siliceous sponges as well as various trace fossils. The sediments record a major regional transgression, which resulted in the flooding of extended, previously subaerially emerged sabkha and carbonate platform areas across the whole of Svalbard (Hellem, 1980; Steel & Worsley, 1984; Blomeier et al., 2011). Above the Vøringen Member, the strata of the Kapp Starostin Formation are arranged into a number of informal, local members (Fig. 2). Within the type area of the formation in western central Spitsbergen, the Svenskeegga and Hovtinden members were proposed by Cutbill & Callinor (1965). The lower Svenskeegga member, which comprises the strata above the Vøringen Member, consists mainly of spiculitic cherts, silty shales and bioclastic limestone beds at the top. The overlying Hovtinden member is composed of shales, siltstones, sandstones and sandy limestones, laterally grading into the Revtanna member in southern Spitsbergen (Bellsund) and into the Stensiöfiellet member in central Spitsbergen (inner Isfjorden). The latter two members were proposed due to substantial facies changes in the upper part of the Kapp Starostin strata compared with the type area at Festningen (outer Isfjorden). Accordingly, the Revtanna member, proposed by Knag (1980) and defined by Dallmann et al. (1999), comprises siliciclastic-dominated strata, probably originating from the erosion of the neighbouring Sørkapp–Hornsund High. The member consists of three coarsening-upward sequences, each beginning with limestones and grading up via dark shales or siltstones into clayey, glauconitic sandstones. The Stensiöfjellet member, proposed and defined by Dallmann et al. (1999), is also marked by the predominance of siliciclastic material, characterised by distinct green, glauconitic sandstones (with up to 30% glauconite), sandy spiculitic cherts and sporadic brachiopodal limestone horizons.

On Nordaustlandet, parts of the Kapp Starostin strata are arranged into the Palanderbukta and Selanderneset members, which have only a local importance and are not correlated with the local members on Spitsbergen. Whereas the Palanderbukta member, defined by Lauritzen (1981), is dominated by fossiliferous, sandy limestones with minor sandstones and cherts, the overlying Selanderneset member, originally introduced as the Selander suite by Burov et al. (1965), consists mainly of sandy fossiliferous limestones and glauconitic sandstones, which form three separate successions divided by minor chert intercalations. However, it is rather hard to comprehend the internal lithological arrangement and boundary definitions of the various members in the field. In addition, neither the stratigraphic constraints of the informal members nor the overall lithostratigraphic framework of the Kapp Starostin Formation are yet fully understood.

Age constraints of the Tempelfjorden Group have been proposed by Forbes et al. (1958), Gobbett (1963), Cutbill & Callinor (1965), Szaniawski & Malkowski (1979), Biernat & Birkenmajer (1981), Nakamura et al. (1987), Stemmerik (1988), Nakrem (1988, 1991, 1994), Nakrem et al. (1992), Mangerud & Konieczny (1993), Buggisch et al. (2001) and Chwieduk (2007) based on small foraminifers, bryozoans, brachiopods, corals, conodonts and palynomorphs. Accordingly, sedimentation of the Vøringen Member started at sometime in the late Artinskian/early Kungurian and continued until the late Kungurian, with the main part of the Kapp Starostin Formation probably deposited in the Guadalupian (Fig. 2).

# Methods

Four vertical sections have been established in key localities in northeastern Svalbard during geological summer fieldwork 2005 to 2007 (Fig. 1). The section sites comprise the stratotype locations for the Palanderbukta member at Zeipelfjella (section Z1) originally described by Lauritzen (1981) and for the Selanderneset member (section E1) at Eremitten (Hellem & Worsley, unpublished). At the section sites, the thickness, colours, lithologies, textures, sedimentary structures and macrofossils of each bed, as well as the overall large-scale stacking pattern of the entire strata, have been documented. In addition to the outcrop investigations, detailed microfacies studies have been carried out and 205 thinsections (Z1: 42, S1: 41, H1: 98, E1: 24) were prepared in order to investigate the microfacies and compositional variations of the strata. The deposits are highly diverse, showing strongly varying proportions of detrital, terrigenous, siliciclastic material (mainly quartz grains) and organic silica (sponge spiculae), as well as skeletal and non-skeletal carbonate components, embedded in carbonate or quartz matrixes and cements. Generally, carbonates with a content of less than 10% detrital quartz grains of the components are described according to the classification schemes of Dunham (1962) and Folk (1959). The description of the mixed siliciclastic-carbonate deposits follows the classification of Mount (1985), based on the ratio of siliciclastic to carbonate material. Siliciclastic sediments, consisting almost entirely of detrital quartz grains (>90%), are classified after Wentworth (1922). The frequency of the various components and matrix is estimated using visual comparison charts and is described after the following key: abundant (>60% of whole rock), frequent (60-40%), common (40-20%), occasional (20-5%), rare (<5%).

# Facies Analysis

Based on the field data and the findings of the microfacies studies, the strata of the Kapp Starostin Formation are arranged into four main facies associations. In the following, all facies are described, their spatial and regional occurrence indicated and their environmental significance discussed.

#### 1 Sandstones (Figs. 3A, 3B)

Description: Massive, thin- to medium-bedded sandstone beds and lenses predominantly show clear green colours, in addition to whitish and ochre colorations. Locally, the generally highly porous sediments are characterised by abundant Zoophycos or Skolithos burrows. Abundant, sand-sized, subangular to well-rounded, single-crystal quartz clasts are typically densely packed, forming a clastsupported fabric. Occasionally to frequently occurring, ruditic skeletal fragments of mainly thick-shelled brachiopods are locally embedded in the commonly well-sorted sediments. Rare to occasionally occurring glauconite minerals, peloids and larger trepostomebryozoans and crinoid fragments form minor constituents. Non-skeletal grains and skeletal fragments are commonly cemented by one generation of blocky sparite, which is locally replaced by microcrystalline quartz. Within poorly washed areas and burrows, a greyish, micritic to microsparitic matrix is present.

*Spatial and regional occurrence:* Sandstones are common in NE Svalbard, where they form a considerable part of the basal Vøringen Member and characteristic greenish marker horizons in the overlying strata of the Kapp



Figure 3A. Section S1/unit 28: Interbedding of distinct green, glauconitic sandstones (a, facies 1) with brachiopodal limestones (b, facies 2a). Hammer for scale. 3B. Section H1/sheet 65: In addition to abundantly occurring, well-sorted, subangular to rounded, single-crystal quartz clasts, sandstones commonly to occasionally show coarser skeletal fragments of predominantly brachiopods (a: shell fragments; b: spines). 3C. Section S1/ unit 28: In the field, coarse-grained, brachiopodal limestones (facies 2a) are marked by the accumulation of more or less parallel-oriented, ruditic shell fragments, mostly from spiriferids and productids. Due to the local presence of glauconite, the commonly extensively silicified limestones in places show greenish colorations. 3D. Section H1/sheet 63: This brachiopodal rud- to floatstone (facies 2a) consists mainly of the coarse-grained debris of brachiopods (a: shells fragments; b: spines) enclosed by one generation of blocky spar. Here, the original fibrous microstructure of the bioclasts is still preserved. 3E. Section H1/sheet 25: Locally, in situ preserved colonies of trepostome bryozoans occur at the base of the Kapp Starostin Formation (Vøringen Member) in NE Svalbard. The boundary to the underlying Gipshuken Formation is formed by a bored hardground (arrows), which the colonies used as a growth substrate. Hammer for scale. 3F. Section H1/sheet 15: This bryozoan floatstone (facies 2b) is marked by coarse-grained skeletal fragments of timanodictyid (a: Gilmouropora timanodictyid) and fenestrate bryozoans (b), which are embedded in a spiculitic matrix formed by abundant megaspiculae and grey micrite. 3G. Eremitten location: This coarse-grained, crinoidal limestone (facies 2c) commonly shows whitish-weathering stem fragments (a), partly in natural articulation, filigree bryozoan bioclasts (fenestrate bryozoans, arrows) and occasional whole brachiopods (b). The diameter of the coin is about 2 cm. 3H. Section H1/sheet 12: The crinoidal bioclasts (a) of this rudstone (facies 2c) commonly show a syntaxial overgrowth (arrows). The original matrix is entirely replaced by microquartz. Note the trepostome bryozoan fragment (b).

Starostin Formation. The sediments are associated with coarse-grained, brachiopodal limestones (facies 2a) and fine-grained limestones (facies 2e) as well as more rarely with whitish, massive cherts (facies 3a), forming successions up to a few metres in thickness.

*Environmental interpretation:* The calcareous, commonly glauconitic and bioclastic sandstones are interpreted as a typical facies of proximal, shallow-marine foreshore to shoreface areas of the inner ramp, marked by a high siliciclastic input (Fig. 4). Within these nearshore areas, quartz clasts imported from a terrestrial source were constantly reworked and winnowed by tidal currents

and/or wave action above the fair-weather wave base (FWWB), resulting in generally well-sorted and selectively concentrated, detrital quartz grains. The local abundance of benthos, causing increased bioturbation and burrowing of the siliciclastic rocks, has been interpreted as a storm-related feature (pipe rocks; Droser, 1991), which typically forms in the aftermath of storm events by the activity of opportunistic bottom feeders. Characteristic greenish colours of the sandstones are the result of a minor but constant amount of glauconite, the formation of which is usually associated with an open-marine environment, low sedimentation rates, low temperatures and deepermarine conditions (Odin & Letolle, 1980; Huggett & Gale,



*Figure 4.* Schematic shelf model for the Kapp Starostin Formation in NE Svalbard, showing the general distribution of the four main facies (sandstones, limestones, cherts, black shales) across the inner, mid and outer ramp sections. In addition, the distribution of the allochthonous, non-skeletal and skeletal components is indicated. Thick line = rock forming, thin line = significant component, dashed line = accessory. MLW = Mean low water level. FWWB/SWWB = Fair/storm-weather wave base.

1997). This obvious contradiction to the herein proposed sedimentary environment is explained by the postdepositional, early diagenetic formation of glauconite from pore waters seeping through the uppermost horizon just beneath the sea floor. Accordingly, the glauconite minerals formed after the sandstone sedimentation, when deeper, quiet-water conditions marked by low sedimentation rates prevailed (Blomeier et al., 2011).

#### 2 Limestones

Limestones in NE Svalbard generally contain a substantial proportion of detrital quartz clasts and thus constitute sandy, bioclastic limestones to bioclastic sandstones (after Mount, 1985). The commonly strongly silicified sediments are generally thick- to thin-bedded and form laterally persistent successions up to a few metres thick with glauconitic sandstones (facies 1) and light, massive to nodular cherts (facies 3a). Slightly wavy bedding planes are locally replaced by low-relief stylolites. Colours vary from light- to dark-grey to ochre, with brownish or rare reddish discolorations. The limestones contain a diverse, fully heterozoan biotic assemblage consisting mainly of bryozoans, brachiopods and echinoderms, as well as molluscs (bivalves and gastropods), solitary rugose corals and siliceous sponge spiculae as minor elements. Non-skeletal grains mainly consist of quartz sand and peloids, and minor proportions of larger lithoclasts (extraclasts). The depositional area of the limestones generally comprises intertidal to shallow submarine areas of the inner and mid ramp (Fig. 4). Based on the different primary habitat of the various marine benthos, the composition of the limestones is quite variable and indicates deposition within specific zones within these ramp areas. Based on fabrics, grain size and composition of the bioclastic and non-skeletal components, the limestones are arranged into five sub-facies (2a-e).

#### Coarse-grained, bioclastic limestones

These moderately to poorly sorted, highly fossiliferous limestones are generally characterised by the predominance of coarse-grained skeletal components. Strongly varying amounts of the main faunal elements allow the determination of brachiopod- (facies 2a), echinoderm- (facies 2b) or bryozoan-dominated (facies 2c), as well as mixed-bioclastic (facies 2d) limestones.

#### *2a Brachiopod-dominated limestones (Figs. 3C, 3D)*

*Description:* This sub-facies is characterised by the abundant to frequent occurrence of thick-shelled brachiopods, commonly comprising spiriferids and productids, as well as more rare terebratulids, athyrids, rhynchonellids and strophomenids. While the coarsegrained, typically parallel-oriented shell debris is commonly accumulated within massive, laterally extensive brachiopod coquinas, whole specimens are enriched in more rarely occurring brachiopod pavements, commonly a few centimetres to several decimetres thick. Coarse-grained bioclasts of bryozoans, bivalves, gastropods and chaetetids are present in minor amounts, as are commonly strongly altered and Fe-stained lithoclasts (reworked extraclasts from the underlying Gipshuken Formation; Blomeier et al., 2011). The ruditic components are embedded in a micritic, microsparitic, spiculitic or sandy matrix consisting mainly of carbonate mud, sand-sized, edge-rounded to rounded, detrital quartz grains, smaller fragments of brachiopods (filaments), bryozoans and ostracods, as well as sponge spiculae (mostly megaspiculae) and peloids. Within well-washed areas, the components are cemented by blocky sparite. Echinoderm fragments often show a syntaxial overgrowth. The irregularly distributed, arenitic to ruditic components constitute mostly rudstones (minor packstones and grainstones) with a component-supported fabric, but also more loosely-packed floatstones (minor wackestones). Glauconite minerals and mineral separations are rarely present. Fragments and matrix are commonly strongly silicified and the original material is, to varying degrees, replaced by microquartz or multigenerational chalcedony.

*Spatial and regional occurrence:* Brachiopodal coquinas are the typical facies of the Vøringen Member, commonly interbedded with fine-grained, bioclastic, peloidal limestones (facies 2e) or sandstones (facies 1). Higher up in the strata, brachiopod-dominated deposits (mostly coquinas, minor pavements) continue to be important facies elements, commonly occurring within the upper part of individual depositional successions.

Environmental interpretation: Within shoreface to transitional offshore areas, sandy brachiopod shell banks, marked by the accumulation of coarse-grained debris, were a prominent feature of the inner ramp (Fig. 4). The shells, probably washed together during storms, were constantly reworked due to wave action and tidal currents. Grainstone fabrics, the parallel orientation of elongated shells, their commonly high degree of abrasion (roundness) and relatively high sand proportions imply proximal, agitated areas above the FWWB. In contrast, brachiopod pavements, marked by the accumulation of mainly whole specimens, were probably present on more distal and deeper mid-ramp offshore plains between the FWWB and storm-weather wave base (SWWB). During storms, the shells were redistributed across the inner and mid ramp (proximal tempestites), to form the abovementioned brachiopod coquinas within nearshore areas. A minor part of the bioclastic material was apparently also exported onto adjacent outer ramp areas (distal tempestites), where the brachiopods form a minor faunistic element.

#### 2b Bryozoan-dominated limestones (Figs. 3E, 3F)

*Description:* The main constituents of these poorly sorted and commonly strongly silicified skeletal limestones are frequently to commonly occurring fragments of bryozoans (mainly trepostome and fenestrate, minor cystoporate and timanodictyid). These main components are commonly supplemented by echinoderms (crinoids) and megascleres of siliceous sponges (bryonoderm biotic assemblage; Hüneke et al., 2001). In addition, fragments of brachiopods and solitary rugose corals as well as various small foraminifers and ostracodes are occasionally to rarely present. The irregularly distributed, arenitic to ruditic bioclasts are commonly embedded in a micritic to microsparitic and, more rarely, spiculitic, partly Fe-stained matrix. Due to a rather loose component package, a matrix-supported fabric (floatstones to wackestones) commonly dominates, besides occasional rudstone to packstone fabrics. Silt- to sand-sized quartz grains are present in varying amounts (rare to common), although generally fewer and finer as in the brachiopodal limestones (facies 2a). Components and matrix are commonly strongly silicified, with microcrystalline quartz replacing the original skeletal substance and/or embedding material.

*Spatial and regional occurrence:* In NE Svalbard, this facies plays only a subordinate role. Bryozoan-dominated, allochthonous limestones are present within basal sheets of the Vøringen Member, associated with in situ bryozoan patch reefs (Blomeier et al., 2011). Further up in the strata, this facies occurs only sporadically within single limestone units, associated with crinoidal (facies 2c) and mixed-bioclastic (2d) limestones.

Environmental interpretation: Allochthonous, bryozoandominated limestones originate from the erosion of mostly trepostome and fenestrate bryozoan colonies. While the primary habitat of robust, bush-like trepostome bryozoans seems to include mainly the outer reaches of the mid ramp around the SWWB, smaller and more fragile fenestrate bryozoans were mostly distributed across adjacent deepermarine areas of the outer ramp, generally below the SWWB (Nakrem, 1994). From the primary habitat areas, coarse-grained bryozoan debris accumulated within deeper offshore banks and was further transported and distributed by storms, currents and waves. In comparison to the brachiopodal sub-facies (2a), the main distribution area of bryozoan-dominated limestones is located in a more distal shelf position, probably mainly comprising mid-ramp to proximal outer-ramp areas around and below the SWWB. This assumption is supported by the predominantly micritic or spiculitic matrix as well as by a generally finer and lesser proportion of terrigenous, detrital quartz, reflecting more distant, deeper-marine, low-energy conditions during deposition.

#### 2c Echinoderm-dominated limestones (Figs. 3G, 3H)

*Description:* This sub-facies is characterised by the predominance of frequently occurring echinoderm fragments (commonly from crinoids), showing arenitic to ruditic sizes of up to a few centimetres. Together with frequently to commonly occurring bryozoan fragments, crinoids form the main component category of this sub-facies. Brachiopods, ostracods, sponge spiculae as well as rare, small foraminifers and glauconite minerals are minor constituents. The commonly partly silicified

skeletal fragments are poorly sorted and irregularly distributed, mainly forming matrix-supported floatstones (wackestones), in addition to rarer pack- and grainstones (rudstones). The matrix consists mainly of partly silty and Fe-stained micrite or microsparite. In well-washed areas, calcite cements are present, formed mainly by the syntaxial overgrowth of crinoid fragments or blocky sparite. Cements and embedding material are locally replaced by microquartz or chalcedony.

*Spatial and regional occurrence:* Although crinoid fragments are present within all limestone facies as a minor constituent, echinoderm-dominated limestones are quite rare. Associated with bryozoan-dominated (facies 2b) and mixed bioclastic limestones (facies 2d), they are present within the Vøringen Member as well as in individual limestone successions higher up in the strata.

*Environmental interpretation:* The relatively high content of bryozoan fragments within this sub-facies as well as the association with bryozoan-dominated limestones point to the mid ramp as main habitat of the crinoids, including the bryozoan build-ups at the outer edge. In addition, crinoids occur within all limestone sub-facies as minor elements, implying that echinoderms and their bioclasts were widely distributed across the entire shelf. While rare grainstone fabrics reflect proximal, higher-energy areas of the inner ramp, more commonly occurring micritic matrixes imply deposition within distal, low- to moderate-energy areas below the FWWB of the mid ramp.

#### 2d Mixed-bioclastic limestones

Description: This sub-facies commonly comprises deposits that are marked by a highly diverse, heterozoan component composition. The main constituents of these moderately to poorly sorted, skeletal rud- to floatstones consist of fragments of brachiopods, bryozoans, echinoderms and sponge spicules without any dominant bioclast type. Fragments of chaetetids, gastropods and bivalves are locally present in minor amounts as well as brownish carbonate lithoclasts (extraclasts) and smaller peloids. In poorly washed areas, the matrix is composed of partly Fe-stained micrite/microsparite, sand-sized, edge-rounded detrital quartz grains or accumulations of unidentifiable, fine-grained skeletal fragments (filaments). However, most of the inter- and intragranular pore spaces are cemented by blocky sparite or the syntaxial overgrowth of echinoderm fragments. Brachiopod shells, in particular, are commonly silicified.

*Spatial and regional occurrence:* This sub-facies, commonly occurring within the limestone successions of the Kapp Starostin Formation, is marked by a mixture of the most common skeletal fragments and is thus associated with all the other coarse-grained facies types (2a–c).

*Environmental Interpretation:* The highly fossiliferous deposits comprise a fully heterozoan (bryonoderm) biotic assemblage, represented by brachiopods, bryozoans,

echinoderms and/or siliceous sponge spicules. Due to the association with the other facies types, the coarsegrained character of the various bioclasts and the common presence of blocky sparite, sedimentation under highenergy conditions within open-marine and shallowmarine areas of the inner and mid ramp is assumed.

# 2e Fine-grained bioclastic, peloidal limestones (Figs. 5A, 5B)

Description: This facies type comprises generally wellsorted, sandy limestones to allochemical sandstones with arenitic brachiopod shell fragments, peloids and sand-sized quartz grains as the main component categories. Ruditic bioclasts of brachiopods, bryozoans and echinoderms as well as glauconite minerals are occasionally to rarely present. The rather loosely packed and equally distributed components show no preferred orientation and are commonly cemented by one generation of blocky sparite, thus representing grainstones, in addition to more rarely occurring packstones and wackestones, which have a microsparitic matrix. Locally, the sediments show distinct cross-bedding or are intensely bioturbated, marked by abundant Skolithos or Zoophycos burrows with a microsparitic or more rarely spiculitic filling. Locally, the original matrix of these sediments is replaced by microquartz.

*Spatial and regional occurrence:* In NE Svalbard, this subfacies is prevalent within the Vøringen Member, where it is intercalated with coarse-grained brachiopodal limestones (facies 2a) and laterally grades into calcareous sandstones (facies 1), forming the upper unit of storm-related, stacked sediment couplets (Blomeier et al., 2011). Within limestone successions above the Vøringen Member, fine-grained bioclastic, peloidal limestones play only a subordinate role.

*Environmental interpretation:* The fine-grained, wellsorted sediments are interpreted to represent sedimentation within open-marine nearshore areas of the inner ramp. Here, the components were constantly washed and winnowed due to wave action or tidal currents. Grainstone fabrics reflect agitated water conditions around the FWWB. As the upper unit of proximal tempestites (lower member: coarse-grained brachiopodal limestones), they represent sedimentation in periods without storm activity. Considering the relatively high proportion of detrital quartz in connection with the local abundance of various burrows, the sediments are comparable to pipe rocks (Droser, 1991), reflecting the post-storm activity of opportunistic sea-bottom grazers in near-shore environments.

#### 3 Spiculitic cherts

Within the Kapp Starostin Formation strata, spiculitic cherts display the most prominent facies in Svalbard, repeatedly forming successions up to several tens of metres in thickness. The sediments are marked by the accumulation of siliceous sponge needles (megaand microspiculae) and thus display the most obvious products of an immense, biogenic silica production characterising the sedimentation of the formation. During diagenesis, the biogenic silica was remobilised and skeletal and matrix substances were replaced to different extents, leading to a commonly strong silicification not only within the cherts themselves but also within all other facies of the strata. Due to their colour, sedimentary structures and association with other facies, two sub-facies of cherts are distinguished.

#### *3a Light, massive to nodular cherts (Figs. 5C, 5D)*

*Description:* This sub-facies forms medium- to very thick-bedded chert units marked by generally light-ochre, whitish and more rarely light-greenish colours. The sediments are massive to nodular with discontinuous, strongly curved bedding planes, probably due to intense bioturbation and subsequent diagenetic pressure-dissolution processes. The main component category is formed by abundantly occurring, densely packed, monazon megaspiculae, in addition to rarer microspiculae. Other biota consist of arenitic to ruditic fragments of brachiopods (also commonly whole biogens), bryozoans, crinoids and more rarely solitary corals, which are irregularly distributed and commonly enriched in laterally

Figure 5A. Section Z1/sheet 23: This medium-bedded, well-sorted, sandy limestone (facies 2e) shows distinct cross bedding. The greenish colour is due to the presence of glauconite. Magnifying glass for scale. 5B. Section S1/sheet 43: This sandy, bioclastic grainstone (facies 2e) shows strongly reworked, elongated brachiopod shell fragments (a) and subangular to well-rounded, sand-sized quartz clasts (b) as the main component categories. 5C. Section Z1/unit 38: Interbedding of thick-bedded, whitish, nodular to massive cherts (facies 3a, a) and medium-bedded, grey limestones above (b). The irregular, wavy bedding planes are probably the result of diagenetic pressure/dissolution processes. 5D. Section H1/sheet 42: Abundant monazon megaspiculae commonly form light-coloured, massive to nodular cherts (facies 3a). The spicules, shown in various longitudinal and cross sections are marked by a central canal, which in places is filled by authigenic glauconite (arrow). The original matrix is replaced by brownish chalcedony. 5E. Section S1/sheet 35: Monotonous succession of dark, thin-bedded cherts (facies 3b) with black-shale partings on the slightly wavy bedding planes. Hammer for scale. 5F. Section S1/sheet 24: Dark cherts (facies 3b) are marked by the accumulation of sponge spiculae, which consist mainly of microspiculae in addition to macrospiculae. The darker micritic areas (a) of this spiculitic packstone probably represent flattened, micrite-filled burrows. 5G. Section H1/units 69/70: Light-coloured, massive cherts and greenish sandstones (facies 3a, 1; a) are overlain by dark, wavy-bedded cherts with shale partings (facies 3b, 4; b). Rusty discolorations due to the weathering of pyrite reflect condensation and low sedimentation rates at the boundary of the two units, which is interpreted as a sequence boundary between two sequences. 5H. Section S1/Vøringen Member: The upper part of the member (a), comprising glauconitic sandstones (facies 1), coarse-grained, sandy limestones (facies 2a, d) and light cherts (facies 3a), is capped by a distinct black-shale horizon, forming the basal sheet of the overlying sequence (b).



restricted horizons or lenses within the cherts. Detrital quartz grains form a minor constituent and glauconite minerals are rare. The sediments are generally marked by an intense bioturbation mostly by variously oriented, single tubular burrows, backfilled with dense micrite or spiculite. A component-supported fabric (packstone) dominates due to the accumulation of sponge spiculae, in addition to matrix-supported areas (wackestones, also in burrows). Bioclasts as well as pore spaces are generally strongly silicified, often consisting of multigenerational chalcedony or microcrystalline quartz.

*Spatial and regional occurrence:* Light-coloured, massive to nodular cherts are the most prominent facies of the Kapp Starostin Formation in NE Svalbard. The sediments repeatedly form thick units within individual depositional cycles and are mainly associated with strongly silicified, skeletal limestones (facies 2a–e) and glauconitic sandstones (facies 1).

Environmental interpretation: Light-coloured cherts most probably formed on vast offshore plains above the SWWB, comprising distal inner-ramp areas (offshore transition) and the entire mid ramp (Fig. 4). Due to the predominance of siliceous sponges, the sediments within these areas consist mainly of their spiculae, which accumulated after the disaggregation of the skeletons. Bioclasts as well as whole biogens of minor biota, such as brachiopods, trepostome bryozoans, echinoderms and solitary corals are embedded within the cherts and partly form laterally restricted accumulations, washed together by waves, tidal currents or storms. Oxygenated sea-bottom conditions combined with agitated water conditions might also be the reason for the generally lighter colours of this chert sub-type, causing a lack of fine-grained, suspended and organic matter. An intense bioturbation probably emphasised by postsedimentary pressure/solution processes led to development of the massive to nodular fabric of these cherts.

#### 3b Dark, bedded to massive cherts (Figs. 5E, 5F)

Description: This chert sub-facies is characterised by generally dark-grey and, to a minor extent, dark-blue colours, commonly forming thick, internally thin- to medium-bedded and more rarely massive successions. The chert units show thinly laminated to thinly bedded black-shale partings on the slightly wavy, discontinuous to continuous bedding planes. Locally, the sediments are marked by an intense bioturbation comprising Zoophycos spreiten, but also various other trace fossils, such as different grazing traces and single tubular burrows (dwelling structures?) of various sizes and orientations. Whole siliceous sponges showing variable, compact to elongated growth forms with diameters of up to several decimetres are locally embedded in situ. Minor components such as arenitic to ruditic skeletal fragments of brachiopods, echinoderms, bryozoans or solitary corals are occasionally to very rarely present, often enriched within individual, massive beds or horizons, constituting spiculitic floatstones marked by brownish or ochre

weathering colours. Generally, the cherts are formed by the accumulation of siliceous sponge spiculae (both megaand microspiculae) and fine-grained lime mud resulting in low-diversity, well-sorted, spiculitic packstones and wackestones. Glauconite grains are rarely to occasionally present. The deposits are affected by a strong silicification, including the complete or partial replacement of the dense, partly silty, micritic matrix, bioclasts and sponge spicules by microquartz.

*Spatial and regional occurrence:* While dark cherts form a substantial part of the Kapp Starostin Formation strata within central Spitsbergen, this sub-facies is generally far less common in NE Svalbard, where light-coloured cherts dominate. Dark cherts are commonly associated with black shales, which form thin partings on the bedding planes.

*Environmental interpretation:* This sub-facies reflects distal, deep, outer-ramp areas, characterised by quiet-water, low-energy conditions far below the SWWB (Fig. 4). A low-diversity biotic association is represented by the widespread occurrence of siliceous sponges and the burrows of various bottom feeders, reflecting mostly oxygenated sea-bottom conditions. The original, micritic matrix probably formed due to the constant accumulation of fine-grained, suspended matter, filling the interspaces between the sponge spicules. During storm events, skeletal fragments (mainly brachiopods, bryozoans and echinoderms) as well as fine-grained lime mud were imported from more proximal, inner- and mid-ramp areas via distal tempestites.

#### 4 Black shales

*Description*: Dark-grey to black shales occur either as very thin partings or medium-bedded, massive or internally laminated horizons. A lamination results from the repeated lateral accumulation of silt-sized quartz grains within even finer-grained terrigenous material. This primary structure is locally obliterated by an intense bioturbation, predominantly displayed by *Zoophycos* spreiten. In addition to occasionally to rarely occurring sponge spicules and glauconite minerals, arenitic to ruditic skeletal fragments or whole brachiopods are rarely present.

*Spatial and regional occurrence:* In NE Svalbard, black shales appear only locally at the base of the stacked depositional cycles. Here, the very fine-grained sediments are commonly associated with dark, bedded cherts (subfacies 3b), forming either discrete horizons or thin linings on the bedding planes of the cherts.

*Environmental interpretation:* Black shales are interpreted as the most distal facies, restricted to deep-marine areas of the outer ramp (Fig. 4). This depositional environment is characterised by quiet-water conditions far below the SWWB and a continuous background sedimentation consisting of very fine-grained terrigenous material (suspended matter). At the sea-bottom, variable oxygen levels prevailed through time. The preservation of a horizontal lamination points to oxygen-depleted conditions, whereas abundant burrows and bioturbation resulted in a massive texture, and indicate the presence of bottom-feeding organisms under oxidised sea-bottom conditions.

### Ramp model

#### Palaeoenvironmental reconstruction

The overall depositional setting of the Kapp Starostin Formation corresponds to an open-water, intermediate- to high-energy, temperate to cold, mixed siliceous-carbonate shelf (Malkowski, 1982; Ehrenberg et al., 2001; Hüneke et al., 2001; Blomeier et al., 2011). In NE Svalbard, the shelf can be separated into inner-, mid- and outer-ramp areas, each characterised by specific facies associations, depositional environments, sedimentary processes and biotic assemblages (Figs. 4, 6).

The model presented herein is a further development of the one introduced by Blomeier et al. (2011), based solely on the strata of the Vøringen Member. Changes comprise the location of the bryozoan build-ups, which have been moved from the inner-/mid-ramp boundary to the outer mid-ramp margin, and the introduction of light cherts (facies 3a) representing the offshore plains of the mid ramp.

#### Inner ramp

The inner ramp comprises intertidal to shallow subtidal areas above and around the FWWB, including foreshore, shoreface and the transition into the more distal offshore plains of the mid ramp (Fig. 6). Within the most proximal

areas (foreshore to proximal shoreface), generally wellsorted and -washed sandstones (facies 1) were constantly reworked and winnowed within shoals and flats under agitated water conditions, due to tidal currents, wave action and periodic storm events. The occurrence of pure sandstones and the substantial sand proportion within the other nearshore lithologies point to a terrestrial source area in the vicinity, and might reflect the uplift and erosion of basement rocks (eastern basement province) in northern Nordaustlandet (Blomeier et al., 2011). Storm events are reflected by the local abundance of Skolithos and Zoophycos trace fossils in the sandstones and finegrained, sandy limestones (facies 2e), interpreted as an increased activity of opportunistic sediment feeders in the aftermath of tempests (pipe rocks; Droser, 1991). These fine-grained sediments commonly form the upper unit of stacked sediment couplets, which comprise coarsegrained brachiopod coquinas (facies 2a) as the lower member (Blomeier et al., 2011). The latter are interpreted as proximal tempestites and reflect the storm-related redistribution of skeletal debris (mainly from thick-shelled brachiopods in addition to minor molluscs, crinoids, sponges and robust, encrusting bryozoans) and nonskeletal components (quartz clasts, peloids, lithoclasts) within sandy shell banks across the shallow-, open-marine flats of the inner and mid ramp. With the transition into adjacent offshore plains, light-coloured cherts (sub-facies 3a) originating from the accumulation of siliceous sponges spiculae, become increasingly prominent.

#### Mid ramp

With increasing water depth in a seaward direction, the inner ramp gradually passes into the open, shallowmarine offshore areas of the mid ramp, roughly between the FWWB and the SWWB (Fig. 6). This shelf zone is



*Figure 6.* Schematic 3D shelf model for the Kapp Starostin Formation in NE Svalbard, comprising a reconstruction of the ramp geometry. The diagram shows the distribution of facies and biota across the ramp. Fossil symbols in Fig. 4

characterised by widespread, locally sandy to silty plains, covered by siliceous sponges that constituted the dominant silica factory of the shelf during the Permian Chert Event. After disintegration of the skeletons, countless siliceous mega- and microscleres accumulated on the sea floor and eventually led to the formation of whitish, massive to nodular, spiculitic cherts (facies 3a). Minor carbonateproducing assemblages gradually changed from mainly thick-shelled into thin-shelled and smaller brachiopods, associated with crinoids, bryozoans and solitary rugose corals. Bryozoans (mainly trepostome) and crinoids are present in probably slightly more elevated areas at the outer mid-ramp margin, forming local build-ups around the SWWB. Their skeletal debris was distributed via storms, waves and tides across the mid-, and innerramp sections and exported onto the outer ramp (distal tempestites). In the process, the allochthonous bioclasts accumulated to form bioclastic limestones (coarse-grained bryozoan and crinoidal limestones, sub-facies 2b, c).

#### Outer ramp

The outer ramp comprises the deepest areas from around to far below the SWWB (Fig. 6). A low-diversity biotic association consists mainly of siliceous sponges, fragile fenestrate bryozoans and various bottom feeders. Under generally low-energy, quiet-water conditions, dark, bedded spiculites (sub-facies 3b) and rare bryozoan limestones (facies 2b) formed due to the mixing of sponge and bryozoan bioclasts with fine-grained matter on the sea floor. Pure black shales (facies 4), displaying a constant background sedimentation and the accumulation of suspended matter, mark areas devoid of any biota. A massive texture of the shales and cherts points to oxygenated sea-bottom conditions and the intense bioturbation of the muddy sediments by sediment feeders, whereas the preservation of a primary, slightly wavy to horizontal lamination might reflect oxygen-depleted conditions during sedimentation. Locally intercalated, thin- to medium-bedded, strongly silicified limestone beds (facies 2b-d), containing coarse-grained skeletal debris (mainly brachiopods, trepostome bryozoans and crinoids) from the mid and inner ramp are interpreted as distal tempestites. They mark the storm-related import of shallow-marine material (components and mud) into the most distal and deepest ramp zones.

## Spatial and temporal ramp development

All sections are located on the Eastern Svalbard Platform, a tectonic element comprising mainly Late Palaeozoic and Mesozoic bedrock east of the Lomfjorden Fault Zone (Fig. 1). The overall, similar, cyclostratigraphic development and sedimentation pattern in all sections implies a coherent, stable shelf area with a rather subdued relief and a ramp-like morphology. The shallow-marine ramp was marked by a siliciclastic input from a terrestrial source area, probably to the north, reflected by the highest sand contents and biggest grain sizes of quartz grains in section Z1. Generally thicker parasequences and a higher proportion of facies representing deeper midramp areas within the H1 and E1 sections imply more accommodation space and thus an inclination of the ramp towards the south.

#### Facies arrangement and cycle stacking pattern

Within all sections, the Kapp Starostin Formation shows a pronounced cyclicity formed by stacked depositional sequences, which consist of conformable successions of genetically related bed sets. Each succession shows a specific order of the herein-defined facies, generally reflecting sedimentation from the deepest, most distal ramp areas at the base to the shallowest, most proximal ramp zones at the top (Fig. 7). Accordingly, the boundaries mark a fundamental and abrupt shift from the shallowest marine environments of the lower succession to the deepest depositional environments of the overlying sequence and thus are regarded as marine flooding surfaces, separating stacked depositional sequences (shallowing-upward sequences). Although no subaerial exposure is recorded at the sequence boundaries, a break in sedimentation during transgression, causing sediment starvation and condensation is commonly indicated by an intensive mineralisation (Fe staining) and glauconitisation of the sediments at the boundaries (Fig. 5G).

The investigated strata are arranged into four parasequences, each marked by an individual facies-set succession, varying substantially in thickness and in the facies and sub-facies which they contain. All sections start with an unconformity at the lower formation boundary to the underlying Gipshuken Formation (Gipsdalen Group), reflecting a fundamental change from warm-water to temperate- and possibly cold-water conditions connected with a major sea-level rise (Beauchamp, 1994; Reid et al., 2007; Blomeier et al., 2011). The lowermost, transgressive sequence, comprising the Vøringen Member (Fig. 5H), is marked by basal hardgrounds locally overgrown by in-situ bryozoan reef knobs, which in turn are embedded and overlain by sandy, skeletal limestones (facies 2a-e), skeletal, glauconitic sandstones (facies 1) and light, massive cherts (facies 3a). The ca. 8 m (section Z1) to 21 m (section H1) thick succession reflects the initial transgression after a prolonged subaerial exposure and hiatus during the Artinskian. The variable sediments reflect mid- to innerramp sedimentation under progressively shallower water depths (Blomeier et al., 2011).

This lowermost sequence is sharply overlain by a distinct black-shale horizon in all section sites (facies 4; Fig. 5H), indicating the termination of shallow-marine shelf sedimentation and the subsequent accumulation of suspended matter under quiet-water conditions below the SWWB. The basal black-shale horizon is followed by a ca. 30 to 40 m-thick succession of spiculitic cherts, which are locally dark and interbedded with shale horizons (facies 3b), or light and massive to nodular (facies 3a), reflecting



**Figure** 7. Simplified section correlation (Z1, S1, H1, E1; Fig. 1) and cyclic arrangement of the strata of the Kapp Starostin Formation. While the Vøringen Member is clearly recognisable, the stratigraphic locations and range of the Palanderbukta and Selanderneset members remain uncertain after current definition (Dallmann et al., 1999). Colours represent bedrock colours. Lithologies correspond to the main facies, which are assigned to specific ramp areas (sandstones = facies 1 = inner ramp, limestones = facies 2a-e = inner to mid ramp, chert 1 = facies 3a = mid ramp, chert 2 = facies 3b = outer ramp, shales = facies 4 = outer ramp). Symbols show the main components of the sediments (legend in Fig. 4). m = mudstone; w = wackestone; p = packstone; g = grainstone; r, f = rud-, floatstone.

deposition on outer to distal mid-ramp areas. Local limestone beds (rud- and floatstones), rich in fenestrate or trepostome bryozoans, minor crinoids or mostly whole brachiopods, are intercalated in the cherts and shales. Upwards, progressively more bioclastic limestones (facies 2a-d) are present, grading into a several-metrethick succession of sandy, brachiopodal limestones and glauconitic sandstones at the top of the sequence, which shows an overall thickness between ca. 36 m (section S1) and 49 m (section H1). The limestone-dominated, upper part of this sequence, also constituting the informal Palanderbukta member (Lauritzen, 1981; Fig. 8), reflects inner-ramp sedimentation. The occurrence of light cherts (section H1) and an increased proportion of trepostome bryozoans (section E1) at the top of this succession might record a renewed deepening of the depositional environment at the transition into the overlying, third depositional sequence.

Separated by another marine flooding surface, the third sequence (ca. 22 m (section Z1) to 35 m (section S1) thickness) shows a basal black-shale horizon and dark, bedded cherts in all section sites, reflecting outerramp sedimentation due to a renewed, relative sealevel rise. The sediments grade into light, massive cherts, upwards increasingly intercalated by sandy limestone beds (brachiopod coquinas) and glauconitic sandstones, probably representing the informal Selanderneset member (Lauritzen, 1981).

The overlying, fourth sequence, from which only the lower part is exposed in sections Z1, S1 and E1, shows a similar facies arrangement, from black shales and dark, bedded cherts in the lower part to lighter, massive or nodular cherts, followed by bioclastic limestones and glauconitic sandstones in the upper part.

Within the lower, chert-dominated parts of the individual sequences, a temporary shallowing is commonly indicated by minor facies variations, such as the deposition of single limestone beds, sandstones or the momentary transition from dark, bedded into lighter, massive cherts. These variations could have been caused by the deposition of distal tempestites, importing shallow-water material from the inner and mid ramp onto the outer ramp (Fig. 7). Another reason might be lower-order, short-term, sea-level fluctuations, superimposed on the higher-order sealevel fluctuations, which are reflected in the parasequence stacking pattern.

As no major tectonic activity has been reported during sedimentation of the Kapp Starostin Formation, the pronounced cyclicity is most likely the result of eustatic sea-level fluctuations, controlling accommodation space and sediment supply, as well as the lateral migration of adjacent ramp (facies) zones. This opinion is in accordance with Beauchamp & Baud (2002), who argued that the cyclicity of the Kapp Starostin Formation and coeval formations in Arctic Canada was driven by substantial ice-volume changes in southern Gondwana, probably accompanied by the development of ice caps in northern high latitudes. Thus, the shallowing-upward facies successions of the individual cycles and the stacking pattern of the latter were probably caused by glacio(?)eustatic sea-level fluctuations of probably the third order, superimposed on a long-term sea-level fall, which lasted from the Mid Permian (Roadian) until the latest Permian (Changhsingian; Haq & Schutter, 2008).



*Figure 8.* Outcrop at Selanderneset (section S1). The strata, showing a thickness of around 100 m, are dominated by light cherts with intercalated shale, limestone and sandstone beds or bed-sets. The Vøringen, Palanderbukta and Selanderneset members, as well as individual sequences (S1 to S4; Fig. 7), are indicated.

## Conclusions

During sedimentation of the Kapp Starostin Formation, a storm-dominated, temperate to cold, mixed siliceous– carbonate shelf prevailed over the depositional area of Svalbard. In the northeast, a shallow, distally deepening, homoclinal ramp developed on a tectonic element, the Eastern Svalbard Platform. With the ramp sloping gently towards the Lomfjorden Fault Zone, siliciclastic material was imported from a terrestrial source area probably to the north.

With increasing water depth and distance to the terrestrial mainland, the ramp is arranged into a nearshore, intertidal to shallow submarine inner ramp, a submarine mid ramp between the FWWB and the SWWB, and a deepermarine, outer ramp with areas below the SWWB, all marked by distinctive biota and sedimentary facies. A varied heterozoan biotic assemblage constituted a major silica and a minor carbonate factory. While the carbonate factory, consisting mainly of brachiopods, bryozoans and echinoderms (with subordinate bivalves, gastropods, chaetetids, foraminifers and ostracods), was restricted to inner- and mid-ramp areas, the silica factory comprised a prolific siliceous sponge fauna, whose primary habitat stretched from the distal inner ramp, across the entire mid ramp to the outer ramp.

On the inner ramp, glauconitic, skeletal sandstones and coarse, sandy brachiopodal coquinas were deposited. These near-shore areas above and around the FWWB were characterised by sand flats, shoals and shell banks, intensively reworked by tides, waves and occasional storms. With the transition into the mid ramp, roughly between the FWWB and the SWWB, broad offshore plains gradually developed with increasing water depth. These were populated by abundant siliceous sponges and more rarely by brachiopods, crinoids, bryozoans and solitary corals. Accordingly, sediments consist mainly of light, nodular to massive cherts besides minor coarsegrained, silicified limestones containing the debris of the carbonate producers. At the boundary to the outer ramp, allochthonous bryozoan and crinoidal limestones, originating from the erosion of robust trepostome bryozoan build-ups, are more common. The outer ramp contains the most distal and deep-marine areas below the SWWB. Dark, bedded to massive cherts and black shales formed there due to the accumulation of enormous quantities of sponge needles and fine-grained, suspended matter under quiet-water conditions. In places, interbedded limestones formed due to the accumulation of mainly fragile, fenestrate bryozoans, as well as bioclasts and lime mud imported via distal tempestites from the innerand mid-ramp areas. Changing sea-floor oxygen levels controlled bioturbation and the preservation of either a primary lamination or massive fabrics in the sediments.

The Kapp Starostin Formation strata display a cyclicity which was formed by stacked shallowing-upward

successions bounded by marine flooding surfaces. The sequences are seen as the result of glacio(?)-eustatic sea-level fluctuations (of probably the third order) superimposed on a long-term sea-level curve, which shows an overall shallowing trend throughout the Mid and Late Permian.

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lsotope chemostratigraphy of high-grade marbles in the Rognan area, North-Central Norwegian Caledonides: a new geological map, and tectonostratigraphic and palaeogeographic implications

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*Figure 2.* Detailed geological map (1:20,000 scale) of the Rognan area, with three geological profiles; A–A', B–B' and C–C'.





